DIRECTION OF EJECTION OF PHOTO-ELECTRONS BY POLARIZED X-RAYS

By Frank W. Bubb

Direction of ejection of photo-electrons by polarized x-rays.—Stereoscopic photographs were obtained, by Wilson's cloud expansion method, which show the ionized tracks of photo-electrons ejected by plane polarized x-rays. The polarized x-rays, scattered by a paraffin block at 90° to an unpolarized primary beam of hard x-rays, were directed horizontally through the expansion chamber of a Wilson cloud apparatus in which they produced the photo-electrons. Exploded tungsten wires furnished the instantaneous illumination of the droplets. The photographs, taken with the plate at 90° to the polarized beam, show two types of asymmetry in the direction of ejection of the photo-electrons. *Lateral asymmetry.* There is a strong concentration of photo-electrons ejected nearly in the direction of the electric vector of the plane polarized radiation performing the ejection. *Longitudinal asymmetry.* Stereoscopic examination of the photographs shows one-sixth of the photo-electrons ejected with a component opposite to the beam, one-third ejected approximately at right angles to the beam, and one-half ejected with a component along the beam. *Theoretical interpretation according to the classical and quantum theories.* The results are in accord with the classical theory. To explain them on the quantum theory we must assume that the quantum is a vector bundle of energy, for it explodes, so to speak, at right angles to its direction of motion.

Introduction

From an examination of one of C. T. R. Wilson's cloud expansion photographs[1] of the ionized tracks of secondary β-particles produced in air by x-rays, A. H. Compton notes[2] that 21 tracks start in directions within 45° of a plane normal to the beam of x-rays, 7 start at about 45° and only three start at angles greater than 45°. This indicates that most of the photo-electrons start nearly parallel to the plane of the electric and magnetic vectors of the radiation. In this connection Compton suggested that "it would be of great interest to examine by this method (Wilson's cloud method) the initial direction of the electrons ejected by polarized x-rays. It seems probable that the direction of ejection should be close to that of the electric vector."

Pohl and Pringsheim's work[3] on the selective photo-electric effect shows that a beam of plane polarized ultra-violet light produces a much larger photo-electric current from certain flat metallic surfaces when the electric force of the radiation has a component perpendicular to the surface than

[1] C. T. R. Wilson, Proc. Roy. Soc. **87**, Plate 8, No. 4, (1912)

[2] A. H. Compton, Bull. Nat. Res. Coun. No. 20, p. 25, (1922)

[3] R. Pohl and P. Pringsheim, Deutsch. Phys. Gesell. Verh. **13**, 474 (June 30, 1911)

when the electric force is tangential to the surface. The supposition that the photo-electrons are ejected nearly parallel to the electric force is in accord with this result, because surely those electrons ejected with a velocity component perpendicular to the surface have better chances of escaping than those have which are ejected tangentially to the surface.

According to the classical electromagnetic theory, the electric force is perpendicular to the direction of propagation of an electro-magnetic wave. If the electric force ejects the photo-electrons, there should then be, in the case of a plane polarized beam, a concentration of photo-electrons nearly in a single direction at right angles to the beam.

The present experiment was performed for the purpose of definitely testing whether there exists any relation between the direction of ejection of photo-electrons and the direction of the electric force of the radiation producing the photo-electrons.

Experimental Procedure

The tracks of photo-electrons ejected by polarized x-rays were photographed by Wilson's cloud method, using the apparatus shown diagrammatically in Fig. 1.

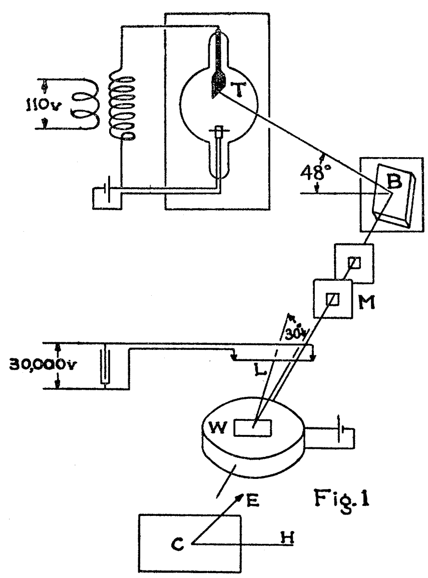

Fig. 1

Fig. 1. Polarized x-rays from the scattering block B pass through the expansion chamber W of a Wilson cloud apparatus and eject photo-electrons nearly parallel to a line CE in the direction of the electric force of the radiation.

An unpolarized beam of x-rays TB, from the tungsten target T of a Coolidge tube driven at about 50 kv and 50 mil-amp., is directed at about 45° to the horizontal upon a paraffin scattering block B. From this scattering block a plane polarized beam of x-rays *BC* proceeds horizontally at 90° to *TB*, through two lead collimating plates *M*, and through the expansion chamber *W* of a Wilson cloud apparatus. The center of a photographic plate *C* is placed in line with and perpendicular to this scattered x-ray. The two lines *CH* and *CE* shown on plate *C* are respectively a horizontal line and a line parallel to the electric force of the polarized beam. The angle between them was about 45°.

On the under side of the plate glass top of the expansion chamber was a transparent conducting gelatin film. On the piston top there was a conducting layer of gelatin blackened with india ink. A constant potential difference of about 60 volts per cm was maintained between the two gelatin layers for the purpose of keeping the chamber free of stray ions until the photograph was taken. The chamber was screened from all but the polarized beam *BC* by placing the Coolidge tube in a lead box, the polarization block in another lead box and by using lead collimators.

To photograph the condensed water droplets along the ionized track of the photo-electron, a very intense instantaneous source of illumination is necessary. Tungsten wires, *L*, .025 mm in diameter and 10 cm long, were stretched between *V* notches and exploded by the current from a condenser of about .04μf capacity charged to about 30 kv by a small transformer having a thermionic valve in circuit. Three wires were generally used for each explosion. Behind the wires was placed a small plane mirror to reflect more light into the chamber. The light entered the chamber through a slot in a piece of black paper covering the chamber top and was inclined at about 30° with the beam of x-rays. It illuminated a small bent wire fastened to the piston which also served as a mark for focusing the camera.

A stereoscopic camera was used. The matched lenses were marked 5.5″ focus, *F* 4.5, and were furnished by the Graf Optical Co. These were set 7.3 cm center to center on the lens board. A piece of black card board extended from the lens board to the plate for the purpose of assuring that each half of the plate was exposed to only one lens. Graflex Seed 60 plates 5″×7″ were found satisfactory.

The timing of the various events of the experiment was accomplished by means of a heavy pendulum which actuated various suitable devices placed in its path. After the room had been darkened and the camera opened, the pendulum was released, resulting in the following events. (1) A weight was released, which pulled the stopper separating the space under the piston from the vacuum chamber, thus producing the expansion. (2) The electric field across the top and bottom of the expansion chamber was removed by breaking the circuit of the battery.

(3) The x-ray tube was started by closing the primary circuit of the transformer. (4) The tungsten wires were exploded thereby illuminating the tracks.

The time intervals between these events were adjusted by trial to give the best photographs; no attempt has been made to calculate them accurately.

Experimental Results

Stereoscopic photographs of the ionization tracks of photo-electrons produced in moist air by plane polarized x-rays were obtained. Some of these photographs are shown in Plate I.

The directions of ejection of the photo-electrons were obtained by measuring the angles made by the initial portions of the tracks with a horizontal line represented by *CH* in Fig. 1. Fig. 2 shows graphically the results of these measurements.

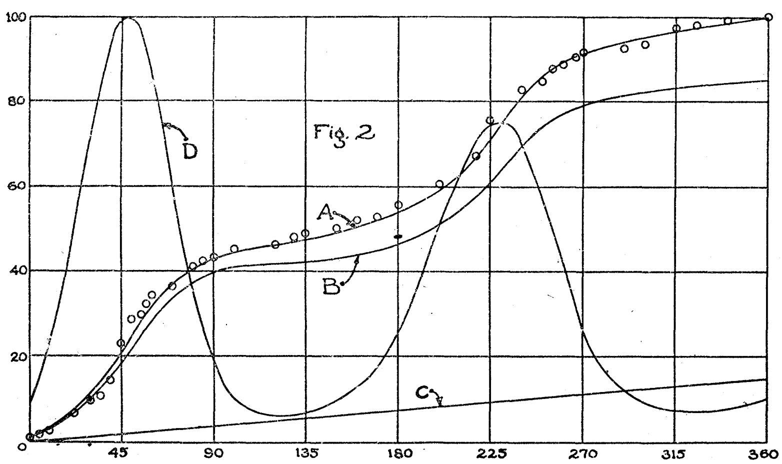

Fig. 2. Two maxima of curve D at 48° and 228° show strong concentration of photo-electrons ejected nearly parallel to electric force of polarized radiation.

In Fig. 2 the abscissas represent the angles, measured counterclockwise from *CH*, of the initial portions of the tracks. In curve A the ordinates represent the relative number of tracks whose initial directions fall between the zero line and the line fixed by the abscissa. For instance the ordinate 43 at 90° is the percentage falling between 0° and 90° of the total number of tracks and not the number starting at 90°. In plotting this curve 156 tracks were considered whose points of origin could be definitely recognized.

Curve B was obtained from curve A by allowing for the non-polarized portion of the beam of x-rays. A scattered (not fluorescent) beam at 90° with the primary is, according to the classical theory, completely polarized. However, compound scattering by thick scattering blocks and the

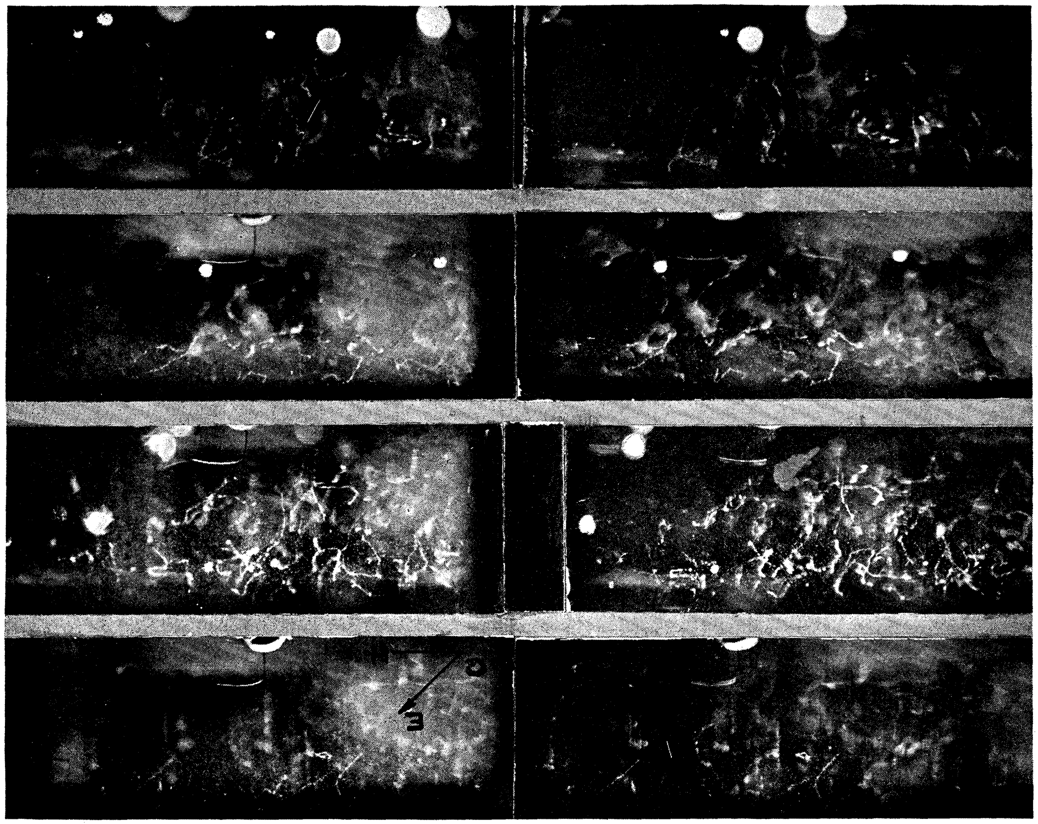

PLATE I

Stereoscopic photographs by Wilson's cloud method of tracks in air of photo-electrons ejected by polarized x-rays. These exhibit: (1) *Lateral asymmetry* in that most of the tracks have initial directions nearly parallel to electric vector of polarized x-rays (see 45° line); (2) *Longitudinal asymmetry* in that most of tracks have forward component with beam. (Use stereoscope.)

necessity of using a bundle instead of a line of x-rays, which renders it impossible to scatter the whole bundle at 90°, have the effect of decreasing the degree of polarization. Allowing for these disturbing factors, A. H. Compton and C. F. Hagenow have shown[4] that hard x-rays, such as were used in these experiments, when scattered at 90° by light elements, are, within the limits of experimental error, completely plane polarized. By comparison with these writers' experiments, it appears that about 85 per cent of the energy of the beam used in the present experiment may be considered as completely polarized, the remaining 15 per cent being unpolarized. If we suppose the 15 per cent unpolarized portion to eject with equal probability in all directions perpendicular to the beam, its effect is shown by the straight line *C* whose ordinate at 360° is 15 per cent of the corresponding ordinate to curve A. The curve B is then obtained by subtracting the ordinates of line *C* from those of curve A.

The curve D is the first derivative of the curve B, and gives the relative number of tracks per degree for all angles between 0° and 360°. The curve D has two well defined lines or humps with maxima at 48° and 228°. These two angles differ by 180° and fix a single line parallel to the electric force of the radiation. Consequently the curve D shows a strong concentration of photo-electrons ejected nearly parallel to the electric force of the polarized beam.

Since these experiments were performed there has appeared an abstract[5] of a paper recently read before the Royal Society by C. T. R. Wilson who discusses some photographs of secondary β-ray tracks which he has obtained by his cloud method. Wilson notes that "partial polarization of the primary beams is indicated by the direction of ejection of a number of the β-particles being in one plane—that containing the direction of the cathode rays in the x-ray tube." Since the plane containing the cathode stream and the beam of x-rays also contains the electric vector of the polarized portion of the radiation, this observation may be taken as confirming the lateral asymmetry brought out by curve D.

Stereoscopic examination of the photographs gives one-sixth of the tracks with an initial component opposite to the beam, one-third approximately at right angles to the beam, and one-half with a component along the beam. In his abstract[5] Wilson remarks that "of the ordinary long range tracks, the majority have a forward component comparable with the lateral component." In this case Wilson's method of taking the photograph with the plate parallel to the beam is better adapted to careful observation than the present method with the plate perpendicular to the beam, although the reverse is true in showing the lateral asymmetry.

[4] A. H. Compton and C. F. Hagenow, Phys. Rev. **18**, 97 (1921)
[5] C. T. R. Wilson, Nature, July 7 (1923)

This effect is probably the same as that first noted by Mackensie[6] and investigated by Bragg,[7] Stuhlmann,[8] Kleeman[9] and Cooksey[10] who found that radiation ejects more photo-electrons from that side of a thin plate from which the radiation emerges than from that side upon which the radiation is incident. Cloud experiments are now in progress in which the ratio of emergent to incident photo-electric current is being measured by counting the forward and backward tracks. In these experiments various gases and various homogeneous x-rays are being used. This method seems likely to give more reliable quantitative results than any method hitherto employed since scattering of the photo-electrons subsequent to ejection is eliminated.

Discussion

The results are in accord with the classical theory. If we adopt the view however that a light quantum consists of a concentrated bundle of energy, such as for example Bragg's "neutron," the present experiment shows that this corpuscle or quantum is not a scalar bundle of energy but has rather definite vector properties. For it explodes, so to speak at right angles to its direction of motion and in a definite plane. Furthermore from polarization phenomena we conclude that such a "vector quantum" once started on its way, maintains its vector properties constant in direction.

It seems likely that the lack of exact coincidence between the direction of the electric force of the radiation and the direction of ejection of the photo-electron may be explained by taking into account the momentum of the electron in its atomic orbit at the instant it is given an impulse in the direction of the electric force of the radiation by the exploding quantum. If we further take into account the forward momentum $h\nu/c$ of the quantum, the longitudinal asymmetry may be explained qualitatively. Calculations based on these ideas together with some experimental evidence in their support will soon be presented.

The writer wishes to make grateful acknowledgment to Professor A. H. Compton for constant advice and assistance, and for placing the facilities of the Washington University Physical Laboratory at his disposal.

Washington University,
St. Louis, Mo.
August 23, 1923.

[6] Mackensie, Phil. Mag. **14**, 176 (1907)
[7] W. H. Bragg, Phil. Mag. **15**, 663 (1908)
[8] O. Stuhlmann, Phil. Mag. **22**, 854 (1911)
[9] R. D. Kleeman, Nature, May 19 (1910)
[10] C. D. Cooksey, Phil. Mag. **29**, 37 (1912)

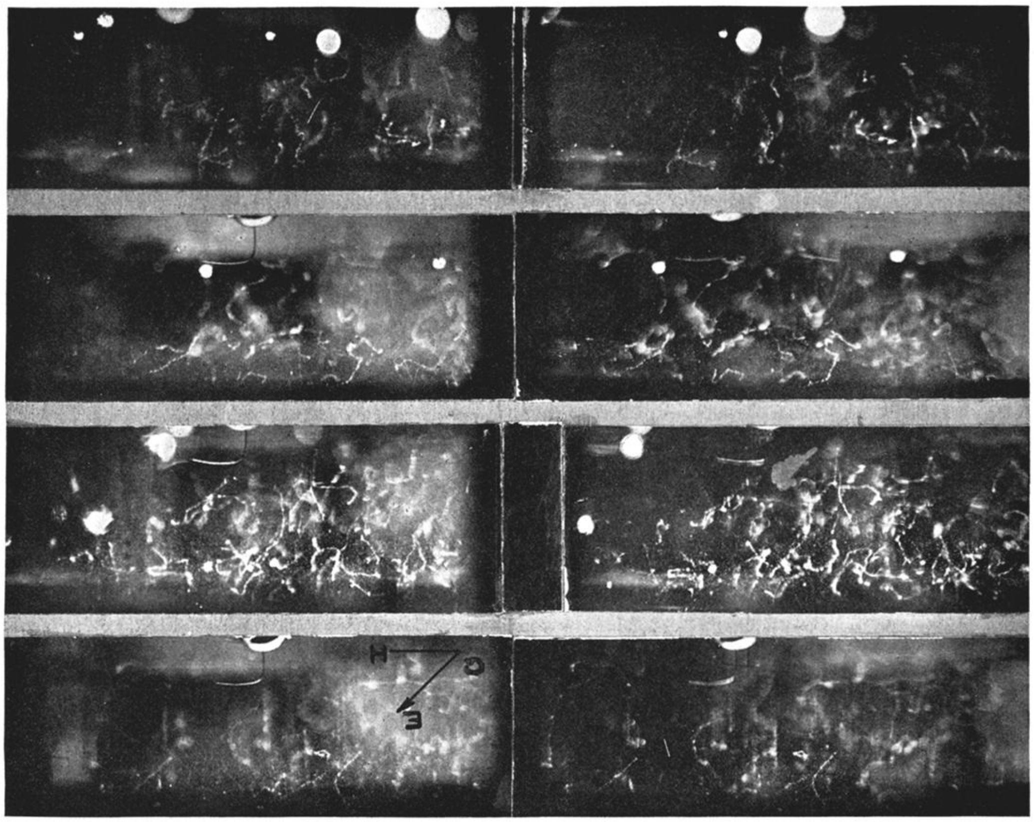

PLATE I

Stereoscopic photographs by Wilson's cloud method of tracks in air of photo-electrons ejected by polarized x-rays. These exhibit: (1) *Lateral asymmetry* in that most of the tracks have initial directions nearly parallel to electric vector of polarized x-rays (see 45° line); (2) *Longitudinal asymmetry* in that most of tracks have forward component with beam. (Use stereoscope.)